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Mars Reconnaissance Orbiter Navigation Strategy for the ExoMars Schiaparelli EDM Lander Mission

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Mars Reconnaissance Orbiter Project

Mars Reconnaissance Orbiter (Mission, Spacecraft and PSO)

The Mars Reconnaissance Orbiter mission launched in August 2005 from the Cape Canaveral Air Force Station arriving at Mars in March 2006 started science operations in November 2006. MRO has completed 10 years since launch (50,000 orbits by Mar 2017) and to date has returned nearly 300 Terabytes of data.

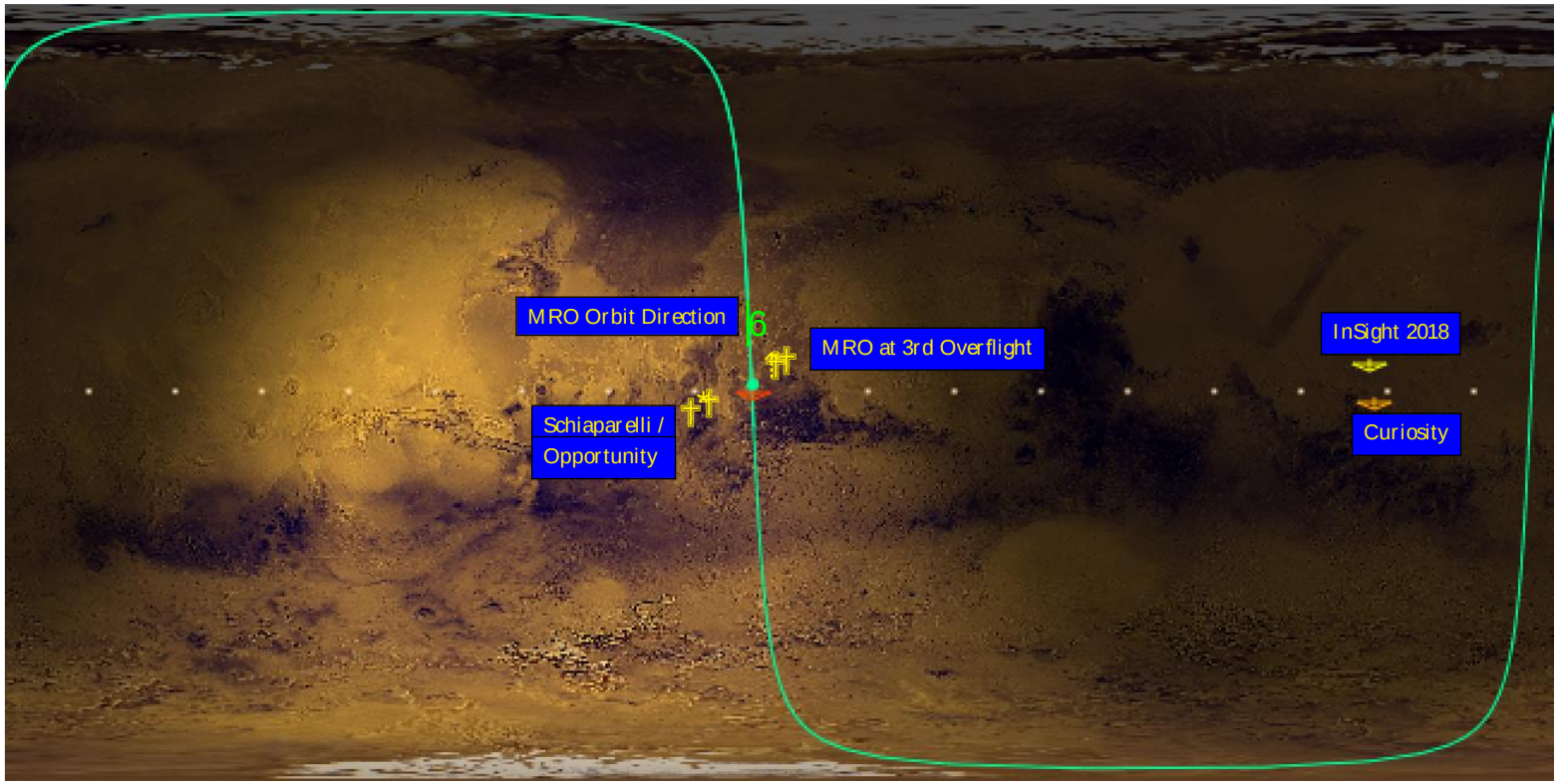
MRO Primary Science Orbit (PSO):

- **Sun-synchronous** orbit ascending node at 3:00 PM ± 15 minutes Local Mean Solar Time (LMST) (daylight equatorial crossing)
- Periapsis is **frozen** about the Mars South Pole
- **Near-repeat ground track walk (GTW)** every 17-day, 211 orbit (short-term repeat) MRO targeting cycle, exact repeat after 4602 orbits. The nominal GTW is 32.45811 km West each 211 orbit cycle (maintained with periodic maneuvers).

MRO Spacecraft:

- **Spacecraft Bus:** 3-axis stabilized ACS system; 3-meter diameter High Gain Antenna; hydrazine propulsion system
- **Instrument Suite:** HiRISE Camera, CRISM Imaging spectrometer, Mars Climate Sounder, Mars Color Imager, Context Camera, Shallow Subsurface Radar, Electra engineering payload (among other instrument payloads)

Schiaparelli Landing Site

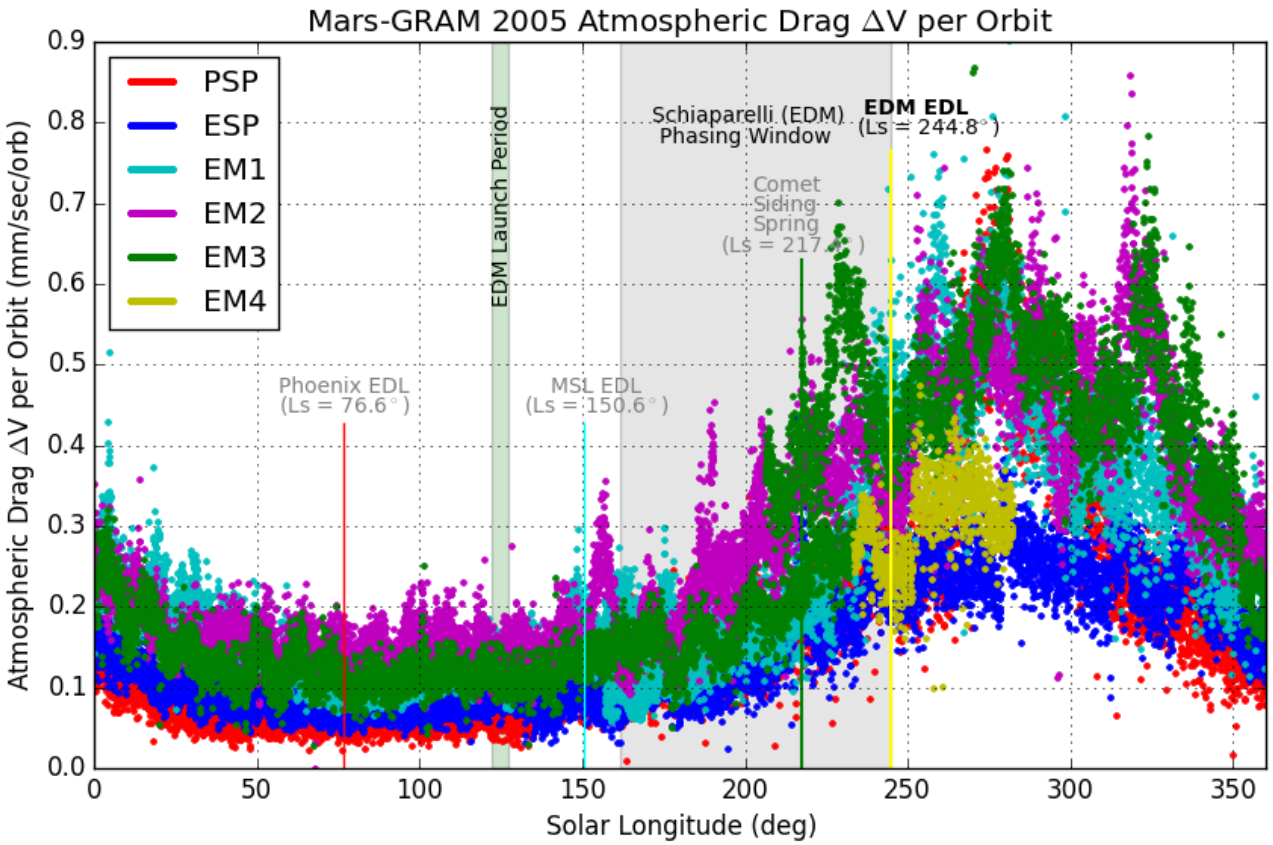


- Schiaparelli landing location: 2.05° S, 6.1° W in Meridiani Planum region, near Opportunity landing site (1.95° S, 5.53° W).
- MRO ground track for the third overflight is shown in green
- Insight (2018) and Curiosity landing site are also shown

Navigation Plan

- The MRO Navigation Team was tasked to develop the maneuver strategy to phase MRO to support ExoMars Schiaparelli EDM lander
  - Overflight Relay Support
    - Schiaparelli's power from battery
    - First 4 sols (prime) out of 2 week support period
    - No EDL support (MRO's orbit orientation cannot support it)
- Phasing Target
  - Per target via EDL Relay Target File
    - Time to cross a set latitude
    - Optimized to support 3rd overflight
  - Navigation Requirement: +/-5 minutes
- Navigation Plan
  - Phasing offset at the time of maneuver planning was 30.6 minutes (early)
    - About 1/4 of the orbit period (112 minutes)
  - 2 pro-velocity maneuvers were planned and implemented
    - Phasing correction in accordance with Navigation uncertainty
    - To increase semi-major axis and the orbit period
    - Slow-down approach also aided GTW

Mars Atmospheric Density Variation



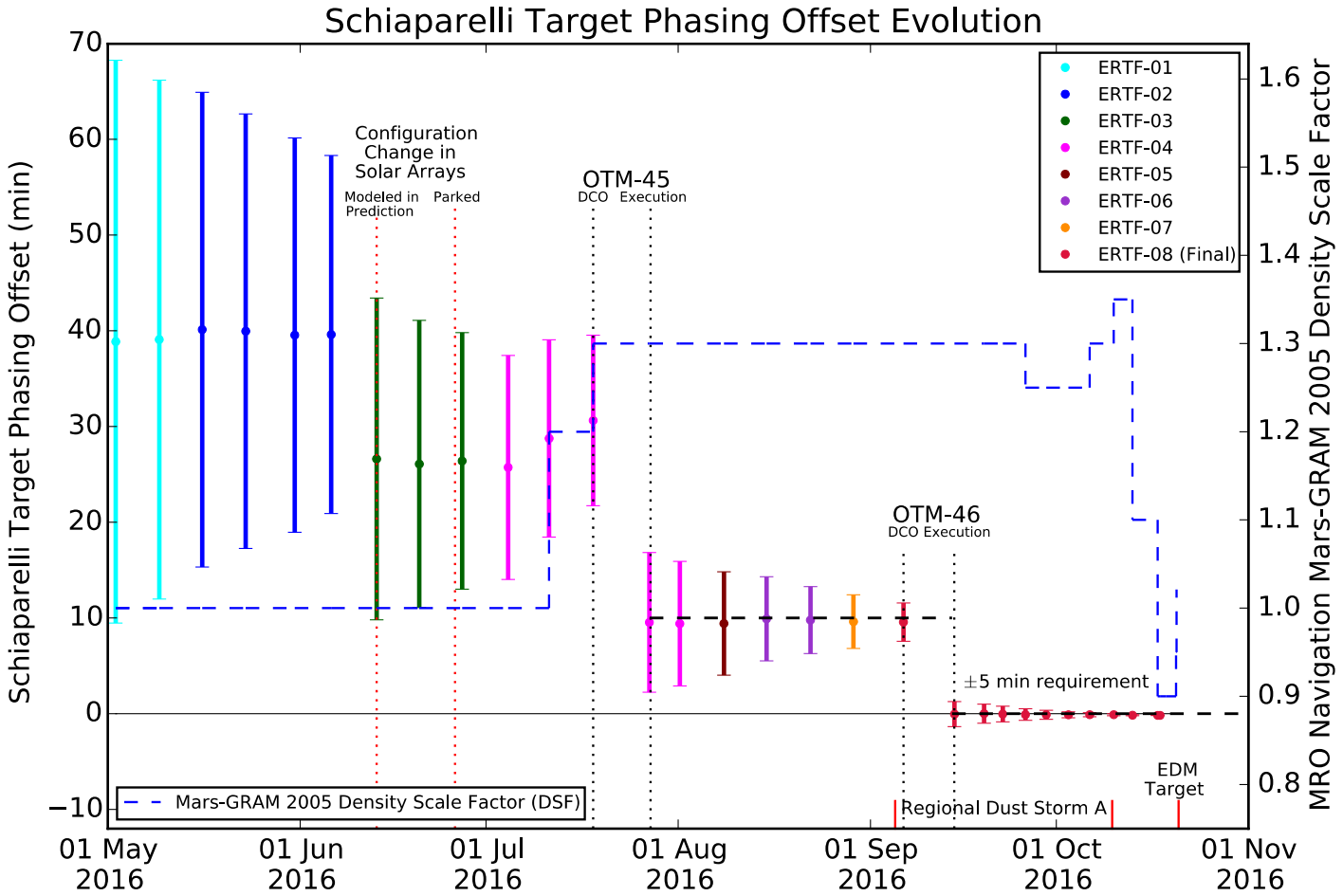
- **Atmospheric Variation:** Biggest navigation error source second only to a significant maneuver execution error
- **Anticipated drag ΔV:** 0.4 mm/s/orbit at the time of maneuvers leading to EDM landing
- **Larger than earlier phasing support:** Phoenix EDL (03/2008) & MSL EDL (08/2012), CSS Risk Mitigation (10/19/14)

Maneuvers and Phasing Corrections

	OTM-45 (OSM-1)	OTM-46 (OSM-2)	OTM-46 Backup	EDM Overflight Target
Event Date	7/27/2016	9/14/2016	9/21/2016	10/20/2016
Days OSM Prior to EDM Target	85	36	29	
OSM Δ V (Designed)	0.1884 m/s	0.2066 m/s	*cancelled*	
Target File	ERTF-04	ERTF-08		ERTF-08
EDM Phasing Offset (Pre-OSM)	30.6 min early	9.6 min early		
EDM Phasing Offset (Post-OSM)	9.5 min early	2.5 sec late		10.4 sec late
EDM Phasing Correction via OSM	20.6 min early	9.6 min early		(reconstructed)
Down-Track Timing Uncertainty (3-σ)	8.9 min	2.0 min	1.5 min	
OD DCO for OSM	7/18/2016	9/6/2016	9/12/2016	
Days DCO Prior to EDM Target	94	44	38	

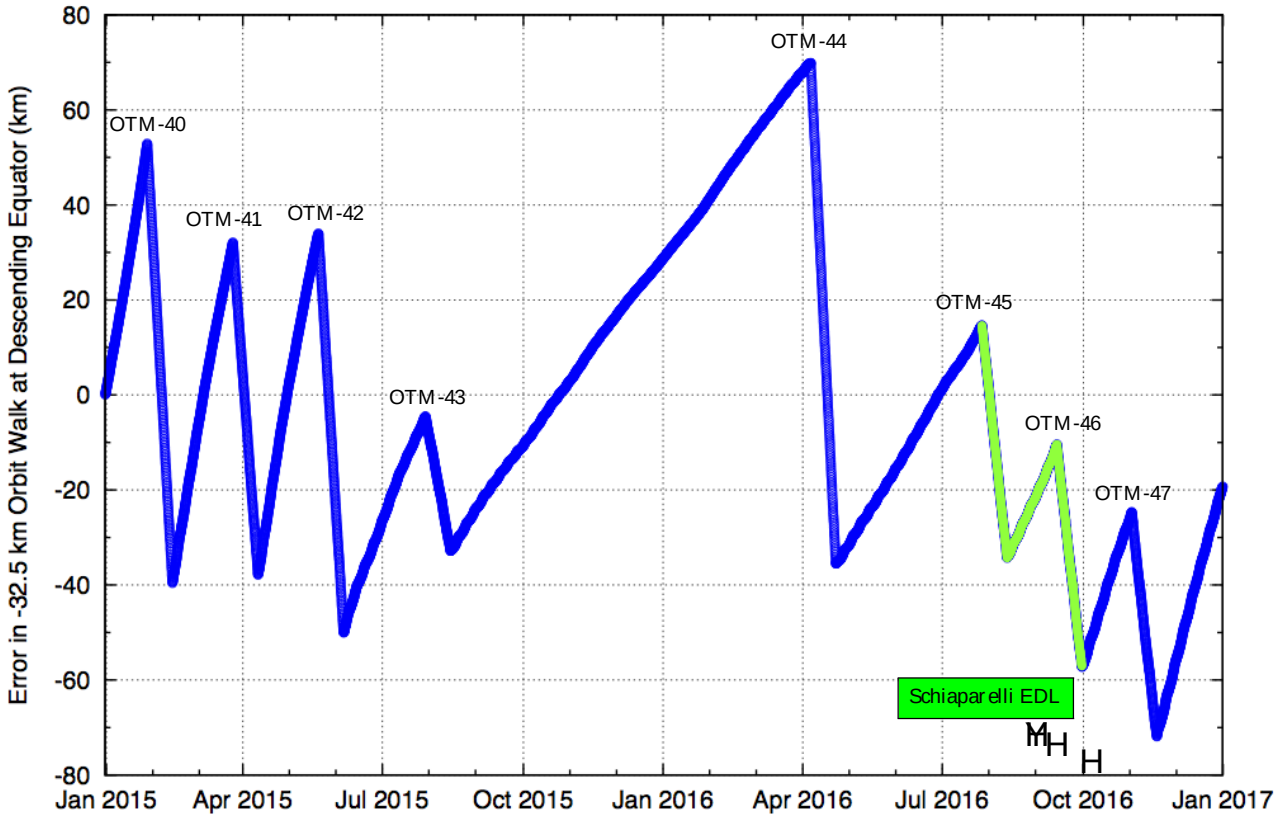
- **Phasing Maneuvers:** 7/27 (OTM-45) and 9/14 (OTM-46)
- **Post OTM-46 phasing offset:**
  - 2.5 seconds but grew to 10.4 seconds at the time EDM landing
  - Final MRO trajectory (9/26) uploaded to EDL lander off by 4.02 seconds

Phasing History



- **Phasing offset monitoring:** Started from 171 days prior to EDM landing
- **Navigation uncertainty:** 9.5 min (OTM-45), 2.5 min (OTM-46)
- **Final phasing offset:** 10.4 sec < 2 minutes uncertainty

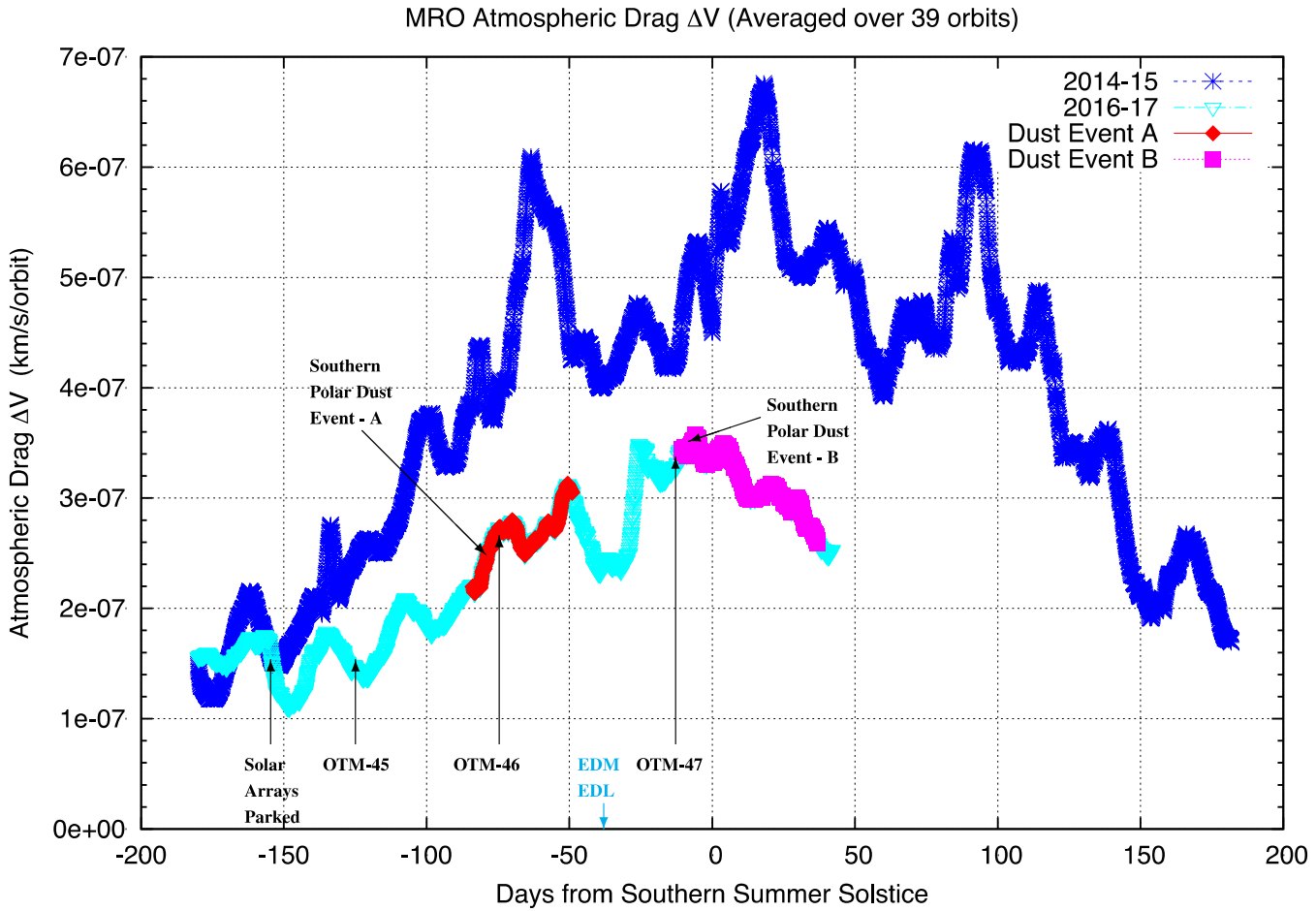
Ground Track Walk at Schiaparelli EDL



Phasing for Schiaparelli:

- Pro-velocity phasing maneuvers (OTM-45 & -46) to EDL
  - GTW error: about -60 km
- Pro-velocity maneuver (OTM-47) to return to PSO

Atmospheric Drag ΔV



- **Maneuver ΔV:** Pro-velocity decreases drag
- **Dust Activity:** Dust Storm adds to the drag ΔV
- **Spacecraft Event:** Fixed Solar Array decreases drag
- Drag lower than previous Mars year, hence the above did not have significant effect

Impact Site by MRO's CTX Camera Before Landing

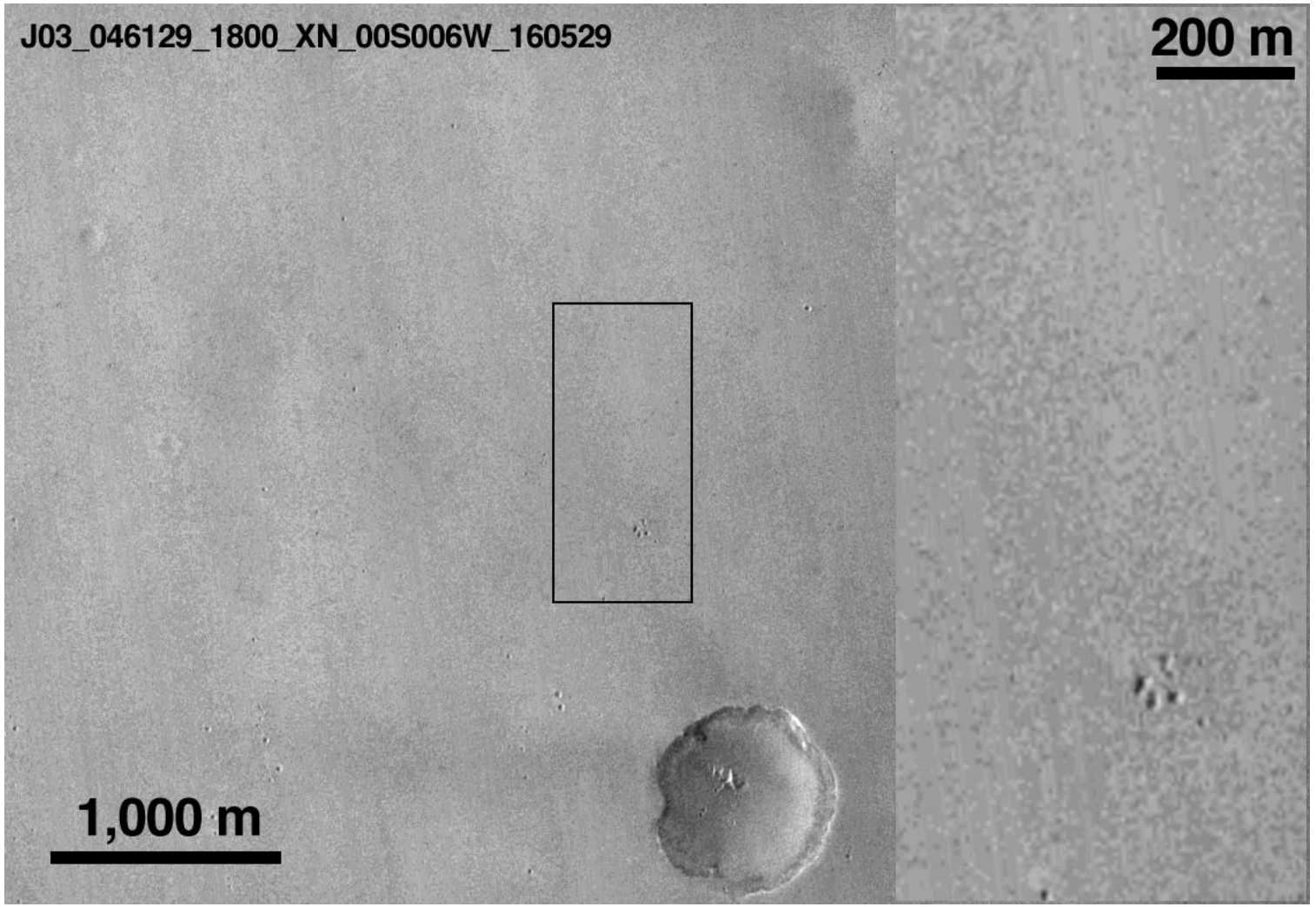


Image of Schiaparelli landing site take by CTX before impact (May 29, 2016)

Impact Site by MRO's CTX Camera After Landing

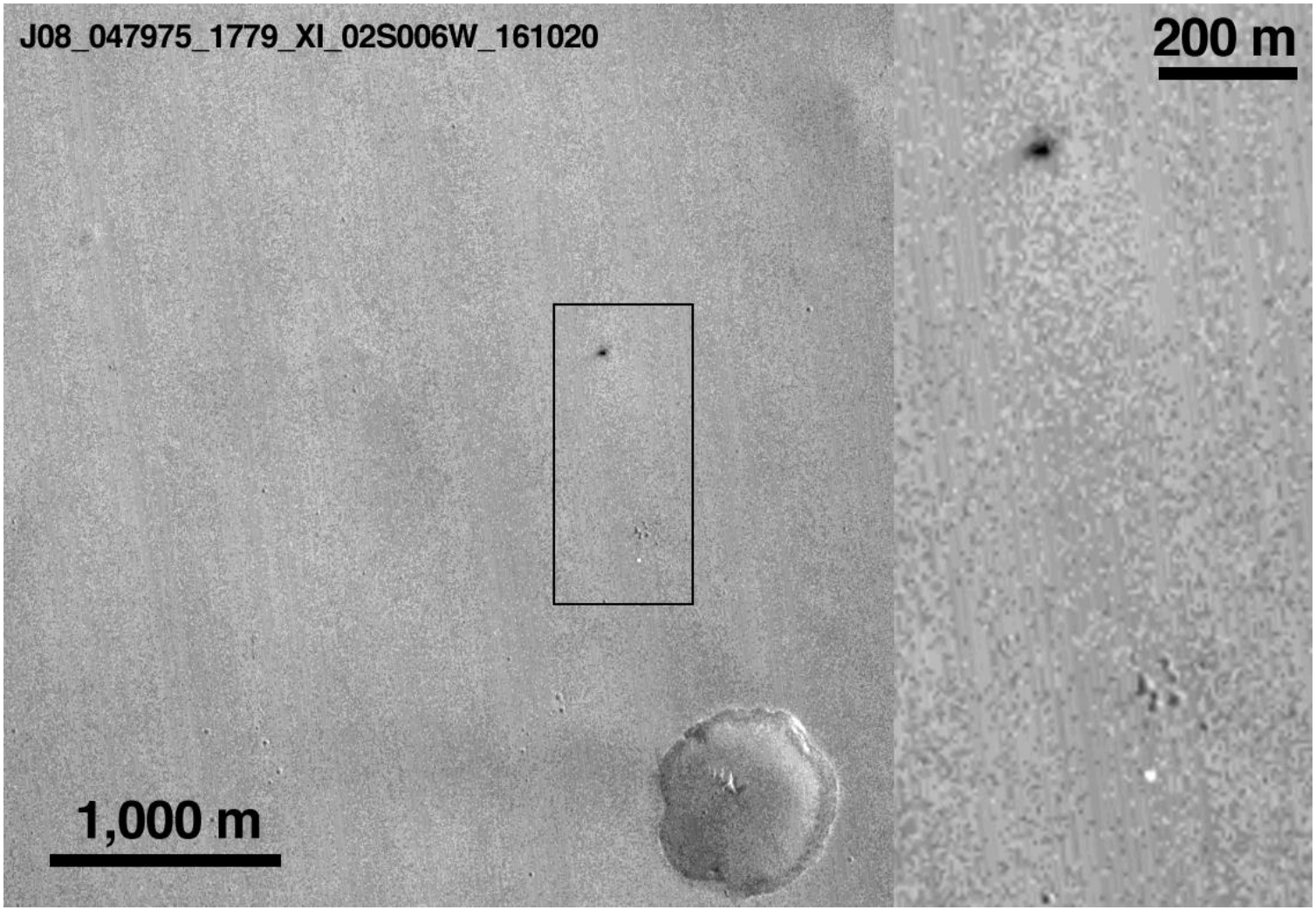
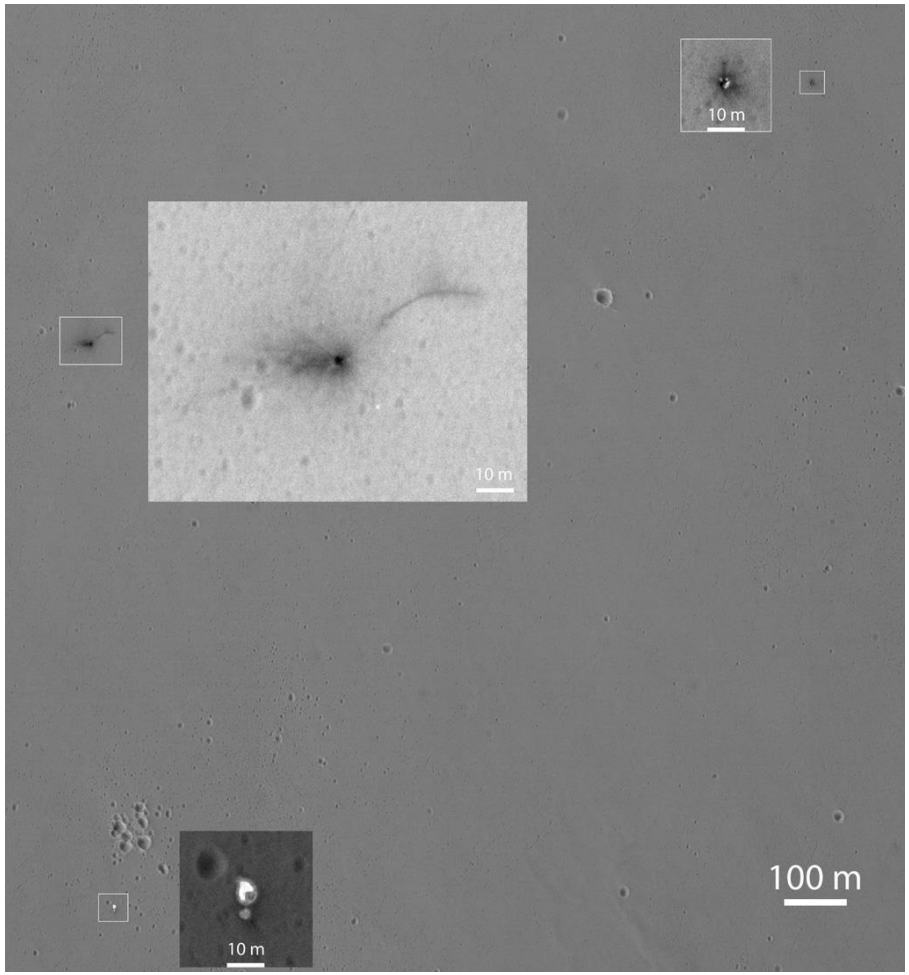
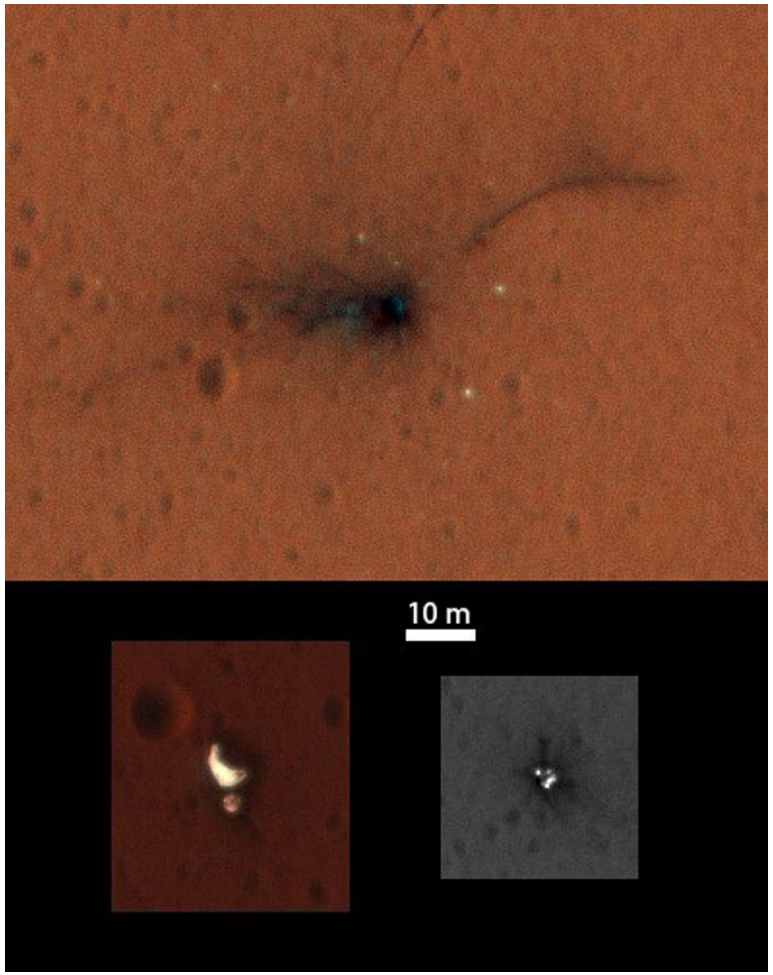


Image of Schiaparelli landing site take by CTX after impact (Oct 19, 2016)

Impact Site Images by MRO's HiRISE Camera



Impact Site Imaged on Oct 25, 2016



Impact Site Imaged on Nov 1, 2016

Summary

- MRO was successfully phased to support Schiaparelli
  - Final phasing offset was 10.4 seconds
  - Offset with the final trajectory uploaded to EDM was 4.02 seconds
  - Well within the ±5 minutes timing requirement given in the EDL Relay Target File (ERTF)
- Post Impact Observation Done by CTX and HiRISE cameras
  - Lander parts located (EDM, lander parachute & heat shield)
- MRO back in nominal Primary Science Orbit (PSO)
  - OTM-47 performed on Nov 2, 2016 to return to PSO
  - Preparing for InSight EDL support in 2018

Backup Slides

EDL Relay Target File (ERTF)

- **Final ERTF (#8) used for final phasing maneuver (OTM-46)**

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EDL RELAY TARGETS FILE (ERTF)
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Data generated on 05 September 2016

ERTF Version: 08

MRO OEM File: ooem_mro_20161019-20161104_20160830traj.txt


*****************************************************************
*   MRO RELAY TARGETS (2000 IAU Mars Fixed)
*   Epoch              : 2016/10/20 17:17:43.789 ET
*   Latitude           : -2.05 deg
*****************************************************************


EDM Data (2000 IAU Mars Fixed)
Entry Epoch               : 2016/10/19 14:43:17.082 ET
     Entry Latitude       : -3.6234 deg
     Entry Longitude      : 342.6699 deg
Landing Epoch             : 2016/10/19 14:48:51.397 ET
     Landing Latitude     :-2.0500 deg
     Landing Longitude    : 353.9000 deg
     Landing Radius       : 3394.071 km
```

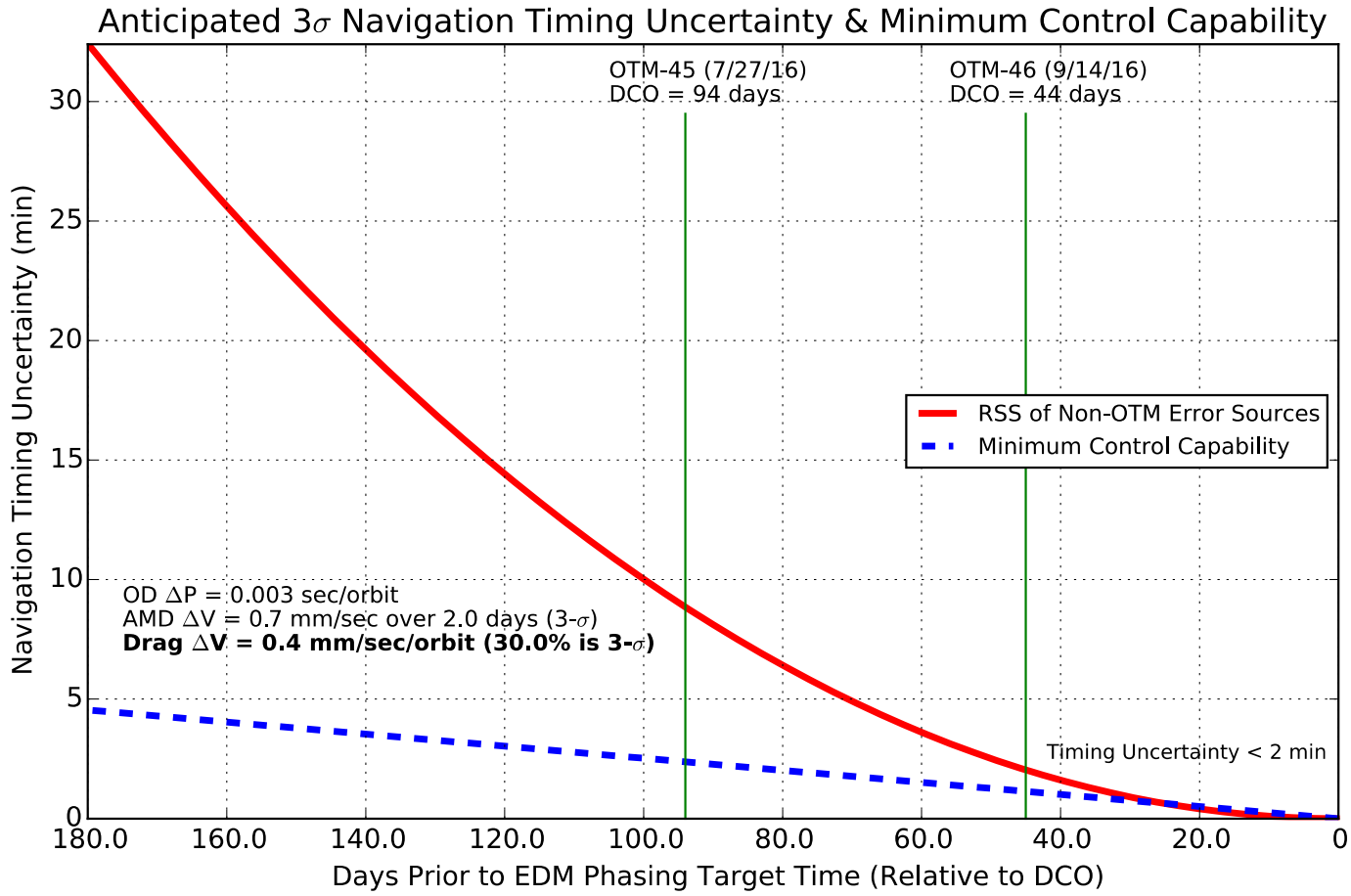
Maneuver ΔV and Direction

Maneuver	Maneuver Epoch (UTC SCET)	Orbital Apsis/ Node	Data Source	ΔV (mm/s)		Right Ascension (deg)		Declination (deg)		Duration (sec)	
				Value	|err|	Value	|err|	Value	|err|	Dur	|err|
OTM-45	27-Jul-2016 12:33:57	Peri	Recon	192.1	3.7	158.54	0.08	36.73	0.01	8.8	0.1
			Design	188.4		158.63		36.72		8.7	
OTM-46	14-Sep-2016 12:57:13	Peri	Recon	210.2	3.6	186.37	0.06	25.45	0.01	9.4	0.0
			Design	206.6		186.43		25.44		9.4	
OTM-46 (backup)	21-Sep-2016 13:16:14	Peri	.... *Contingency maneuver if OTM-46 on 14-Sep-2016 did not execute*								
			Design	257.2		190.28		24.16		11.9	
Schiaparelli Overflight Target Time (Third Overflight): 20-OCT-2016 17:17:43.7890 ET SCET											
OTM-47	02-Nov-2016 12:29:27	Apo	Recon	224.1	4.7	30.69	0.10	−13.25	0.00	9.9	0.1
			Design	219.4		30.79		−13.25		10.0	

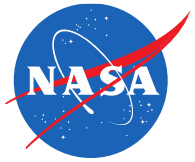
Evolution of Phasing Offset

ERTF	OD Data Cut-off	Days to EDM Target	EDM Phasing Offset + (early) − (late)	3σ Nav. Timing Unc.	ERTF	OD Data Cut-off	Days to EDM Target	EDM Phasing Offset + (early) − (late)	3σ Nav. Timing Unc.	1st Overflight vs. Onboard EDM Timing (Sep 26, 2016)
01	May 2, 2016	171	+38.9 min	29.4 min	07	Aug 29, 2016	52	+9.6 min	2.8 min	
01	May 9, 2016	164	+39.1 min	27.1 min	08	Sep 6, 2016	44	+9.6 min	2.0 min	
02	May 16, 2016	157	+40.1 min	24.8 min	OTM-46 (September 14, 2016)					
02	May 23, 2016	150	+40.0 min	22.7 min	08	**Sep 14, 2016**	**36**	**−2.52 sec**	**1.3 min**	
02	May 31, 2016	143	+39.6 min	20.6 min	08	Sep 19, 2016	31	+0.21 sec	1.0 min	
02	June 6, 2016	136	+39.6 min	18.7 min	08	Sep 22, 2016	28	−2.29 sec	49 sec	
03	June 13, 2016	129	+26.6 min	16.8 min	08	Sep 26, 2016	24	−5.63 sec	36 sec	
03	June 20, 2016	122	+26.1 min	15.0 min	08	Sep 29, 2016	21	−6.57 sec	28 sec	−0.87 sec
03	June 27, 2016	115	+26.4 min	13.4 min	08	Oct 3, 2016	17	−6.99 sec	19 sec	−1.26 sec
04	July 4, 2016	108	+25.7 min	11.7 min	08	Oct 6, 2016	14	−6.15 sec	13 sec	−0.57 sec
04	July 11, 2016	101	+28.8 min	10.3 min	08	Oct 10, 2016	10	−6.20 sec	7 sec	−0.68 sec
04	July 18, 2016	94	+30.6 min	8.9 min	08	Oct 13, 2016	7	−9.58 sec	3 sec	−3.44 sec
OTM-45 (July 27, 2016)					08	Oct 17, 2016	3	−10.41 sec	1 sec	−4.03 sec
04	**July 27, 2016**	**85**	**+9.5 min**	**7.3 min**	08	Oct 18, 2016	3	−10.40 sec	1 sec	−4.01 sec
04	Aug 1, 2016	80	+9.4 min	6.5 min	08	Oct 19, 2016	2	−10.40 sec	0.3 sec	−4.01 sec
05	Aug 8, 2016	73	+9.4 min	5.4 min	08	Oct 20, 2016	0	−10.37 sec	0.02 sec	–
06	Aug 15, 2016	66	+9.9 min	4.4 min	EDM 3rd Overflight Target (October 20, 2016)					
06	Aug 22, 2016	59	+9.8 min	3.5 min	08	**Reconstruction**		**−10.40 sec**	–	**−4.02 sec**

Navigation Uncertainty



- **Phasing Correction:** Only up to what navigation uncertainty allows
- **Minimum ΔV capability:** Maneuver ΔV ≥ minimum ΔV capability (20 mm/s)



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